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Title: Magnetic Quantum Matter in Extreme Magnetic Fields

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Magnetic Quantum Matter in Extreme Magnetic Fields

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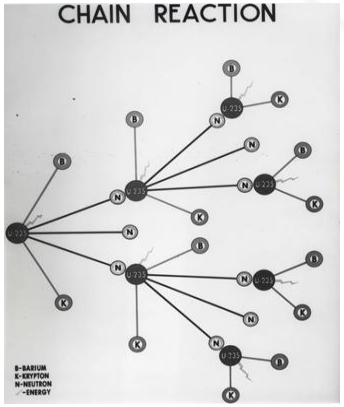
Pulsed Field Facility
Los Alamos, New Mexico 87544, USA

In the Beginning

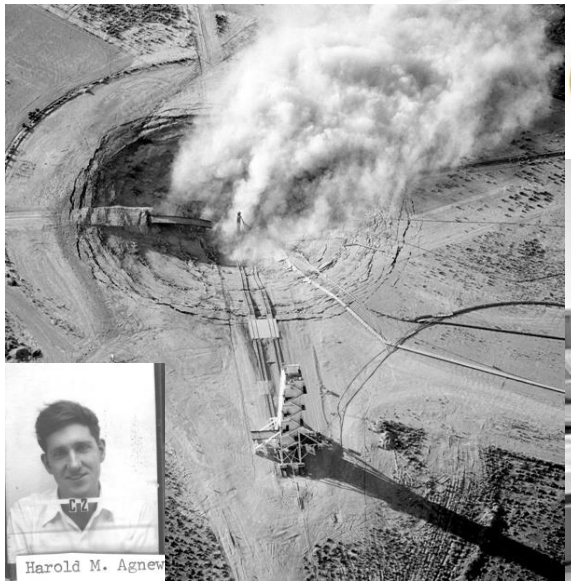
- Fission was first produced in Nazi Germany in 1938
- Einstein, at the urging of Leo Szilard, warned FDR in August 1939
- Japan attacked Pearl Harbor on December 7, 1941
- In April 1943, the first technical conference was held in Los Alamos
- The world's first nuclear test was conducted on July 16, 1945, achieving a yield equivalent to 21,000 tons of TNT
- World War II ends mid August 1945, after atomic bombs dropped in Hiroshima and Nagasaki.



The "Golden Age" of Nuclear R&D

- The nation's stockpile grew from two to 31,255 weapons between 1945 and 1967
- The first thermonuclear test was conducted on October 31, 1952
- CASTLE-Bravo, the nation's largest test, achieved a yield equal to 15 Mega tons of TNT

The 1970-90: A Time of Growth and Change

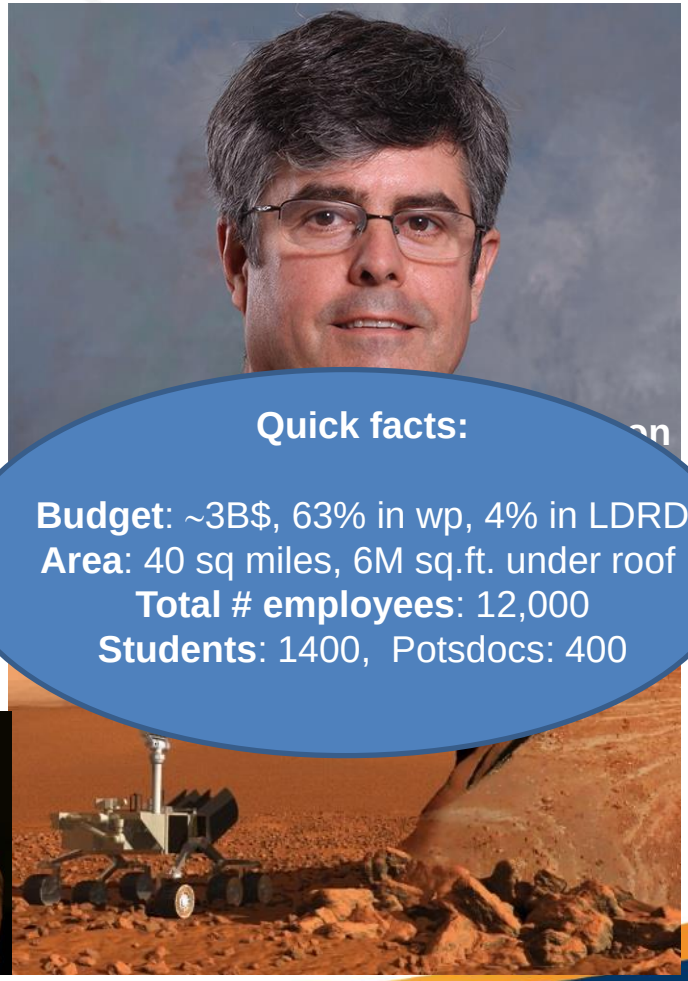


LOS ALAMOS SCIENTIFIC LABORATORY
OF THE UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO

- Under Harold Agnew, the multidisciplinary laboratory of today was born
- The Lab's portfolio grew to include fields of research wholly unrelated to nuclear weapons, such as the development of alternative energy sources
- Safeguards: thousands of IAEA inspectors have received training from Los Alamos
- Last nuclear test took place in 1992
- Environmental restoration became a major priority

Today's Laboratory

- For 20 years the Stockpile Stewardship Program has ensured the safety and reliability of US nuclear weapons without full-scale testing
- The new Trinity supercomputer will be 40 times faster than the Petaflop Roadrunner machine
- LANL scientists are exploring Mars while developing the next generation **Curiosity Rover**
- Project **ATHENA** may soon provide a vastly superior approach for testing new drugs
- Worldwide scientists are doing pioneering work @ LANL Facilities **NHMFL-PFF** and **CINT**



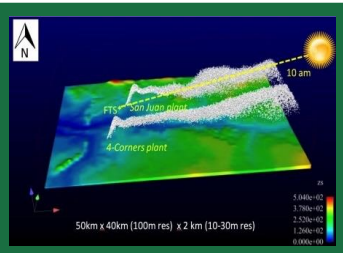
Quick facts:

Budget: ~3B$, 63% in wp, 4% in LDRD
Area: 40 sq miles, 6M sq.ft. under roof
Total # employees: 12,000
Students: 1400, Potsdocs: 400

Four capability pillars define key areas of science, technology & engineering in which today's LANL pursues leadership

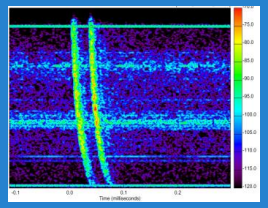
Materials for the Future

- Defects and Interfaces
- Extreme Environments
- Emergent Phenomena



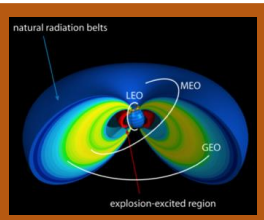
Science of Signatures

- Discover Signatures
- Revolutionize Measurements
- Forward Deployment



Integrating Information, Science, and Technology for Prediction

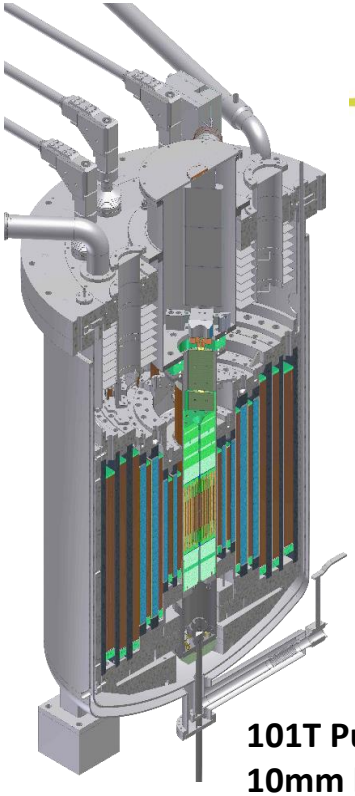
- Complex Networks
- Computational Co-Design
- Data Science at Scale



Nuclear and Particle Futures

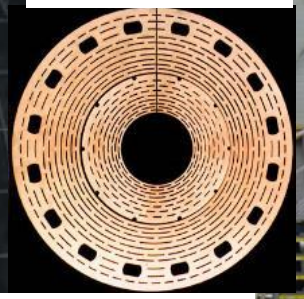
- High Energy Density Physics & Fluid Dynamics
- Nuclear & Particle Physics, Astrophysics & Cosmology
- Applied Nuclear Science & Engineering
- Accelerator Science & Technology

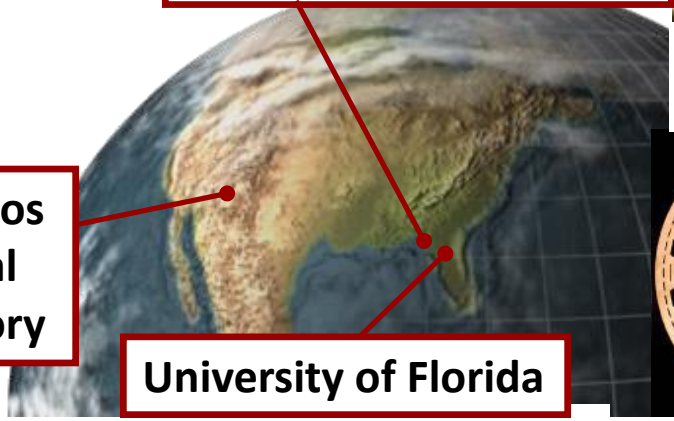
National High Magnetic Field Laboratory



101T Pulse Magnet
10mm bore

45T Hybrid
DC Magnet



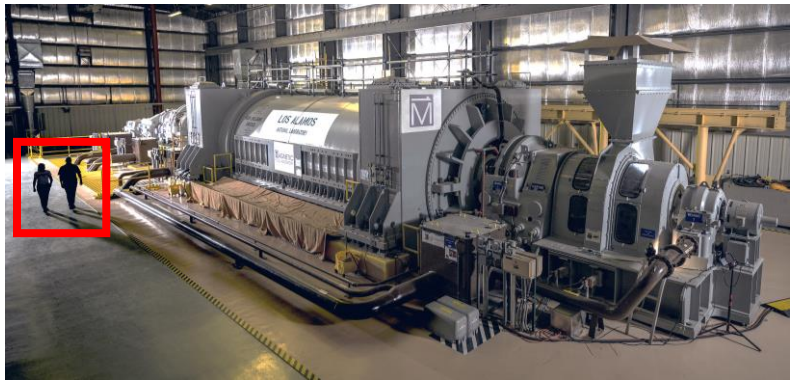


900MHz, 105mm bore
21T NMR/MRI Magnet

Advanced MRI and
Spectroscopy Facility

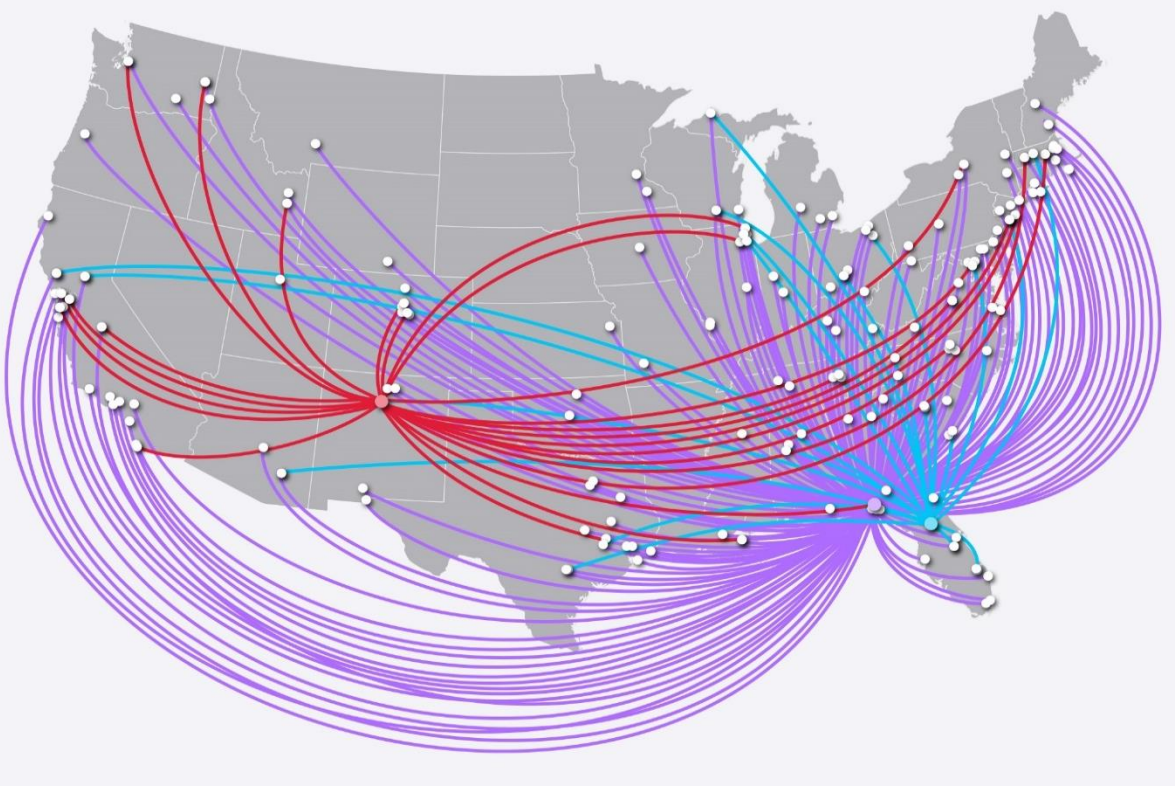
11.4T MRI Magnet
400mm warm bore

High B/T Facility
17T, 6weeks at 1mK



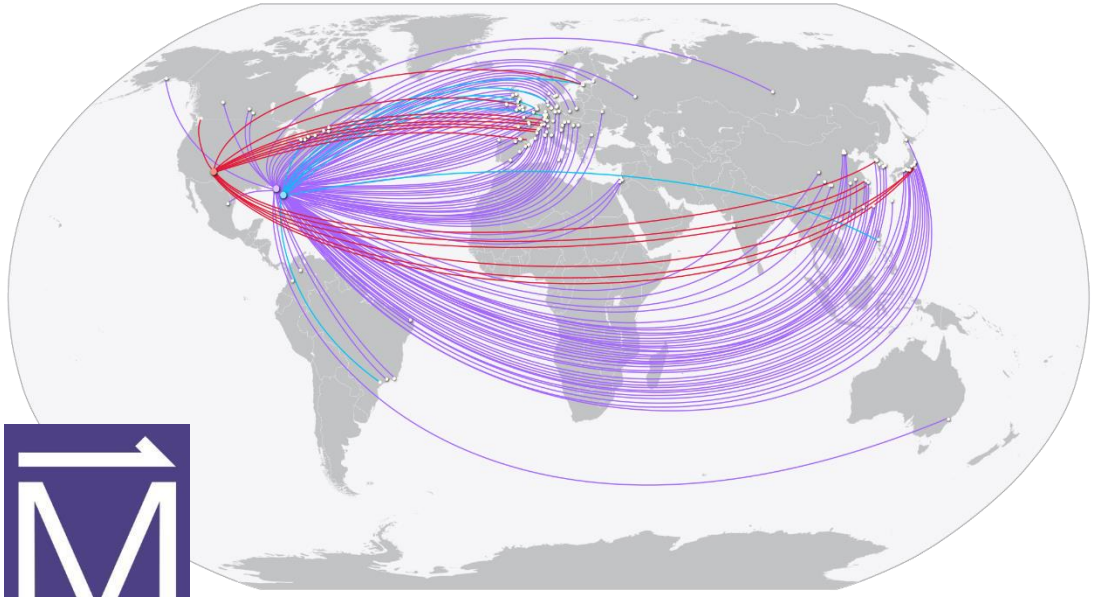
1.4 GW Generator

The MagLab attracts researchers from around the world



In 2017, the MagLab hosted experiments by more than 1800 users from 173 institutions across the United States…

…and a total of 324 institutions from throughout the world.



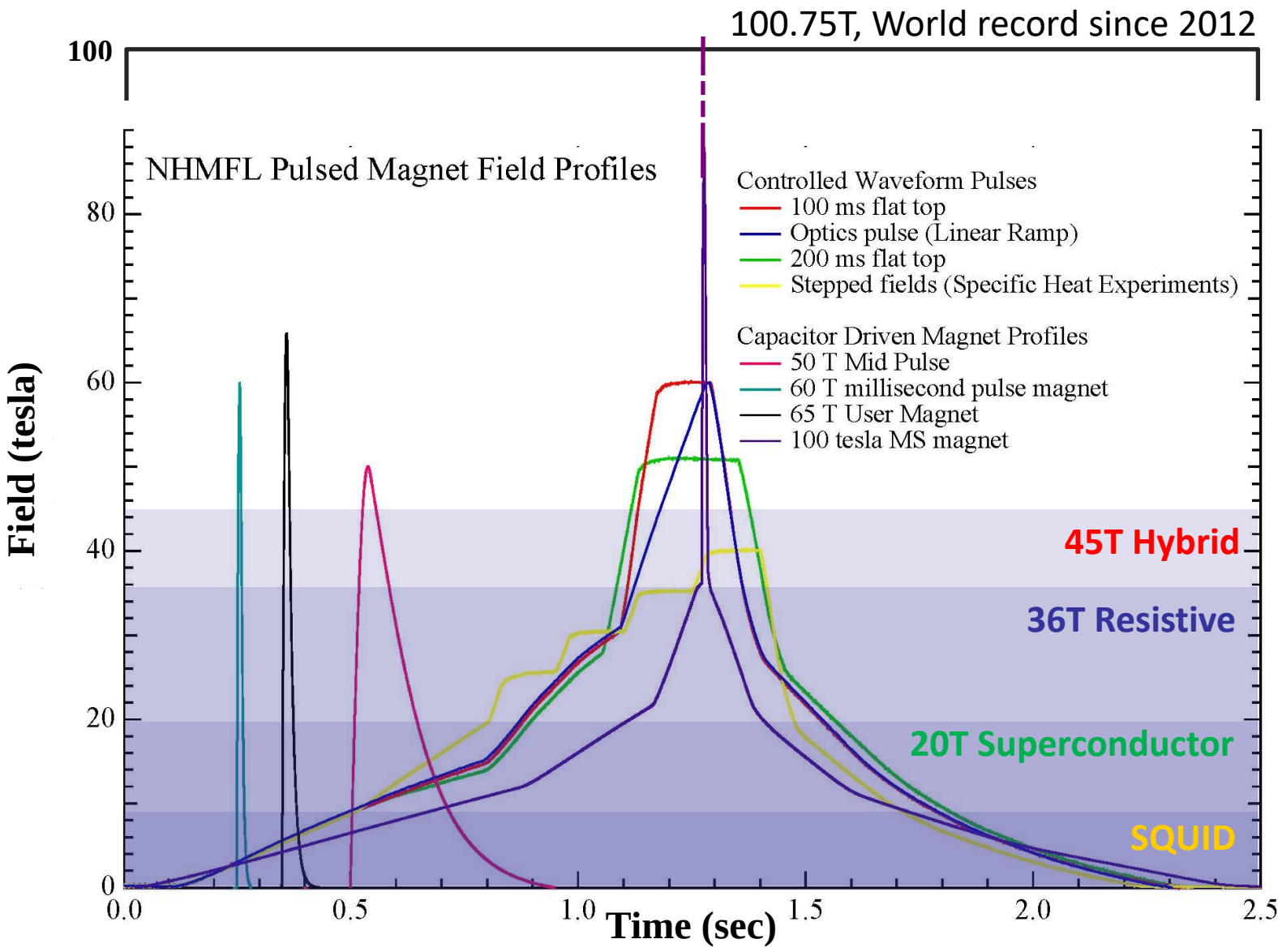
Every year…the MagLab User Program:
helps to train ~225 postdocs
and ~560 graduate students

and publishes ~450 refereed papers:

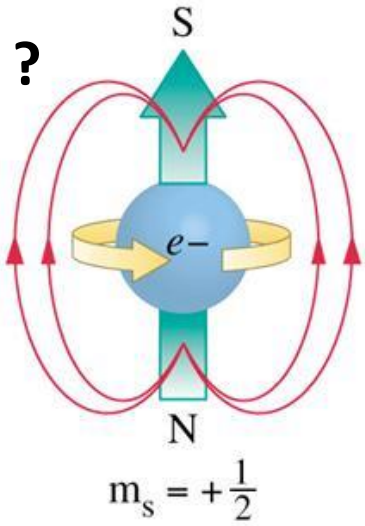
6	*Proc. Nat'l Acad. Sciences*
24	*Nature Journals*
20	*Physical Review Letters*
62	*Physical Review B*
9	*J American Chemical Society*

~ 25% of Principal Investigators are first-time-ever PI's at the MagLab

What are Extreme Magnetic Fields?



What do we mean by “Quantum Matter” ?



Current research of the ‘Quantum’ includes

- **Condensed matter physics**
- **Nano-scale phenomena**
- **Quantum information**
- **Quantum gravity**
- **String theory**

If we restrict “Matter” to the traditional scope of “Materials Science”…
then what do we mean by Quantum Matter?

Materials in which Frontiers of Quantum Mechanics lead to Emergent Properties.
Emergent Properties do not exist within the particle.
They result from collective behavior of large numbers of particles.

These frontiers include:	Emergent properties include:
Strong Electron Correlations	Charge Fractionalization
Topology	Spin, Charge Separation
Frustration	High-Temperature Superconductivity
Quantum Entanglement	Magnetic Bose-Einstein Condensation

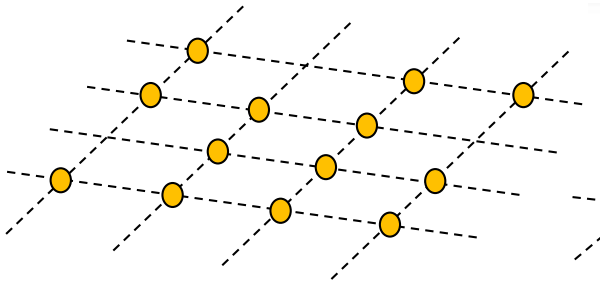
And why? **Fundamental physics, next generation devices, quantum computing.**

For an electron, every material is a different universe.

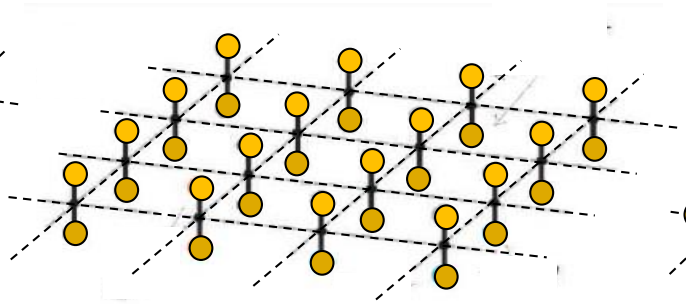
(GSB)

Astronomers Create 8 Million Baby Universes Inside a Computer and Watch Them Grow….
Behroozi et al., *MNRAS*, 488, 3143 (2019).

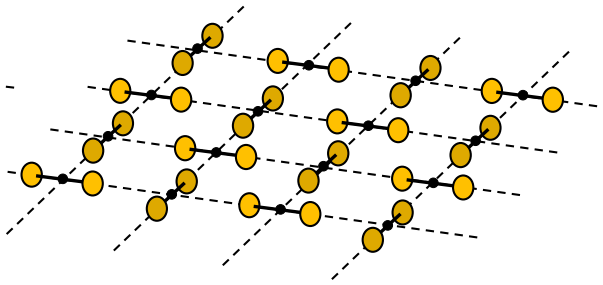
And different electron behaviors lead to different materials' properties.



Single-Layer of Electrons on Copper:
High Temperature Superconductor.
Electricity without Friction



Double-Layer of Electrons on Copper
???????????



Double-density in a single layer
of Electrons on Copper
???????????

1st Copper bilayer linked to Human Invention of Materials (An example from 700 BCE – 200 AD)

Han Purple:
the first synthetic purple pigment.
- Likely made from a mix of barium and copper minerals, quartz, and a lead salt as an extra ingredient that acts as a catalyst and flux.
- The mixture was heated to between 900 and 1000 C.
- Without temperature control Han Blue results, which is closely related to Egyptian Blue ($CaCuSi_4O_{10}$), the oldest known synthetic pigment in the world.

Calcite - $CaCO_3$
Bone White - $Ca_5(CO_3)_2(OH)_2$
White Lead – $2Pb(CO_3)_2 \cdot Pb(OH)_2$

Soot - carbon black

Han Purple* - $BaCuSi_2O_6$**
*** human-made pigment

Cinnabar - HgS
Hematite - Fe_2O_3
Red Lead – Pb_3O_4

Malachite – $Cu_2CO_3(OH)_2$

Han Blue* – $BaCuSi_4O_{10}$**
*** human-made pigment

https://www.youtube.com/watch?v=UcrSV7PQPDQ

1st Copper bilayer linked to Human Invention of Materials (An example from 700 BCE – 200 AD)

Terracotta Warriors (479-221 BCE)

to protect the emperor in the afterlife
…instead of sacrificing real warriors!

Materials Science: Saving Lives for More Than 2000 Years

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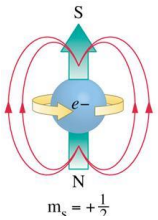
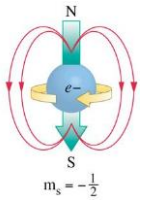
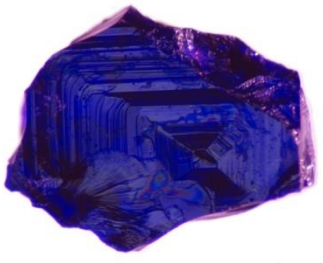
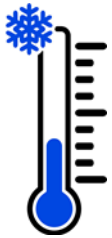
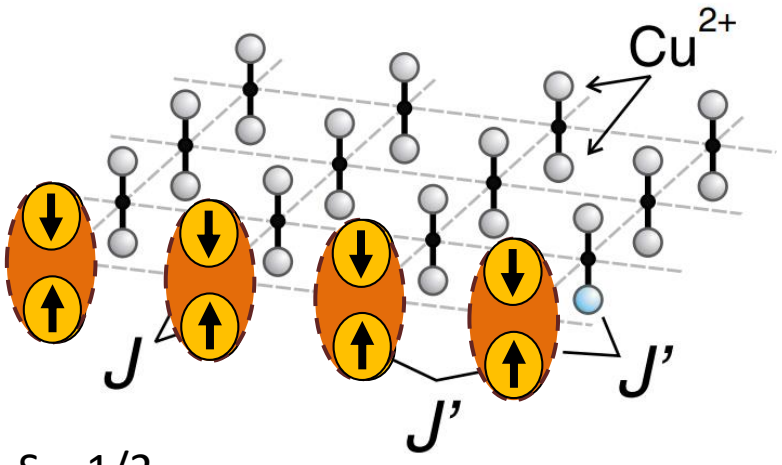
Han Purple is a Strange Universe for Electrons



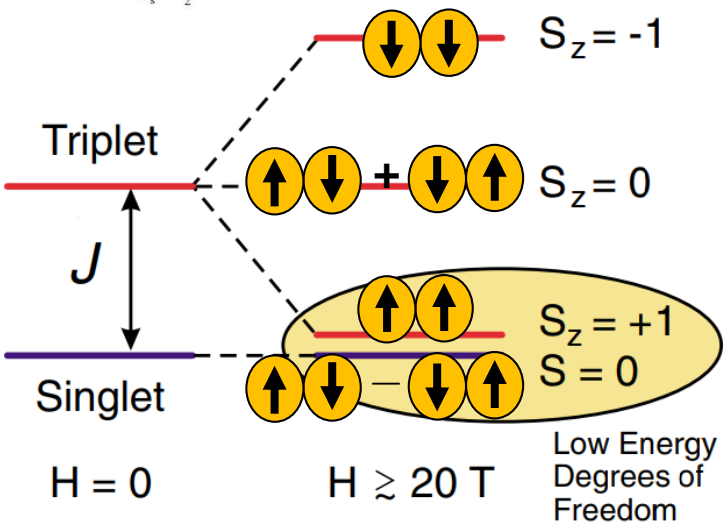








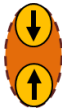
S = 1/2



The electrons pair up on each "barbell" and behave like completely different particles...
A SYSTEM OF S=1 BOSONS

A magnetic field
raises the energy of the Sz=-1 state and lowers the energy of the Sz=+1 state, until eventually the Sz=+1 state becomes degenerate with the singlet state at ~20T.

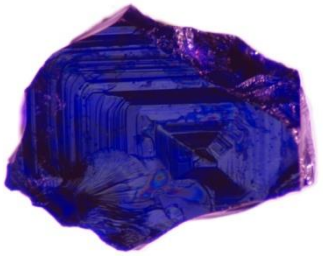
WHICH GIVES NATURE MANY DEGREES OF FREEDOM TO DO SOMETHING INTERESTING…
It makes a gas of bosons, consisting of local spin triplet excitations, called triplons.

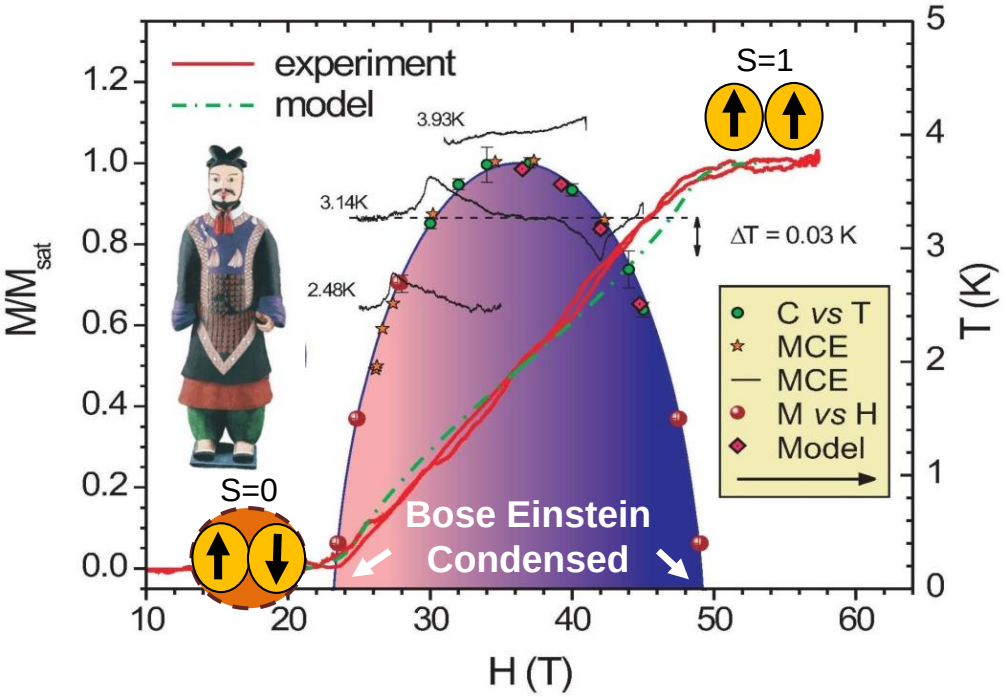


S = 0

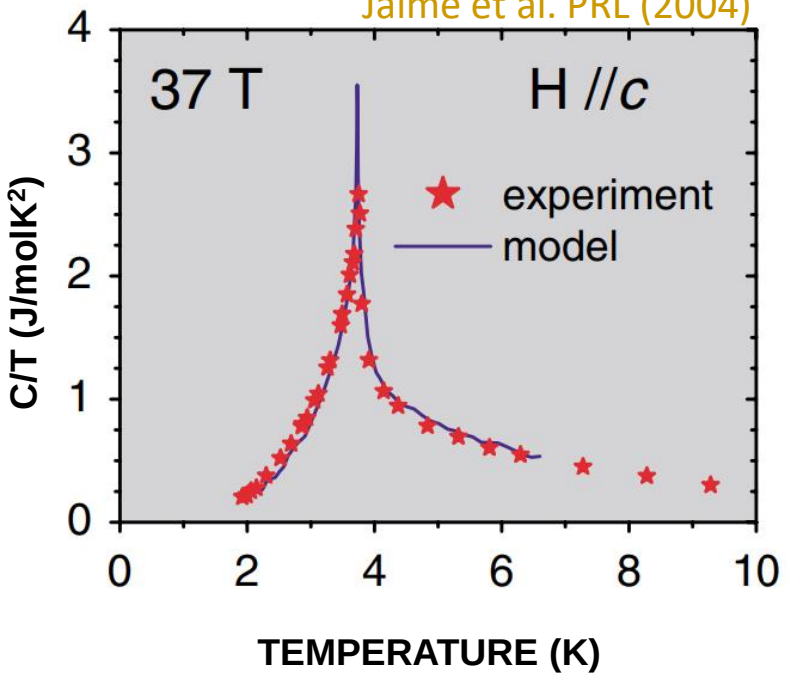
S = 1

Han Purple is a Strange Universe for Electrons





Jaime et al. PRL (2004)



The MAGNETIZATION measures the number of S=1 triplons…
Note that the magnetic field continuously tunes the number (the chemical potential) of the bosons over a wide range of magnetic fields.

$$T_c = [H_c - H_c^0]^{\nu} \;\; ; \; \nu = 2/d$$

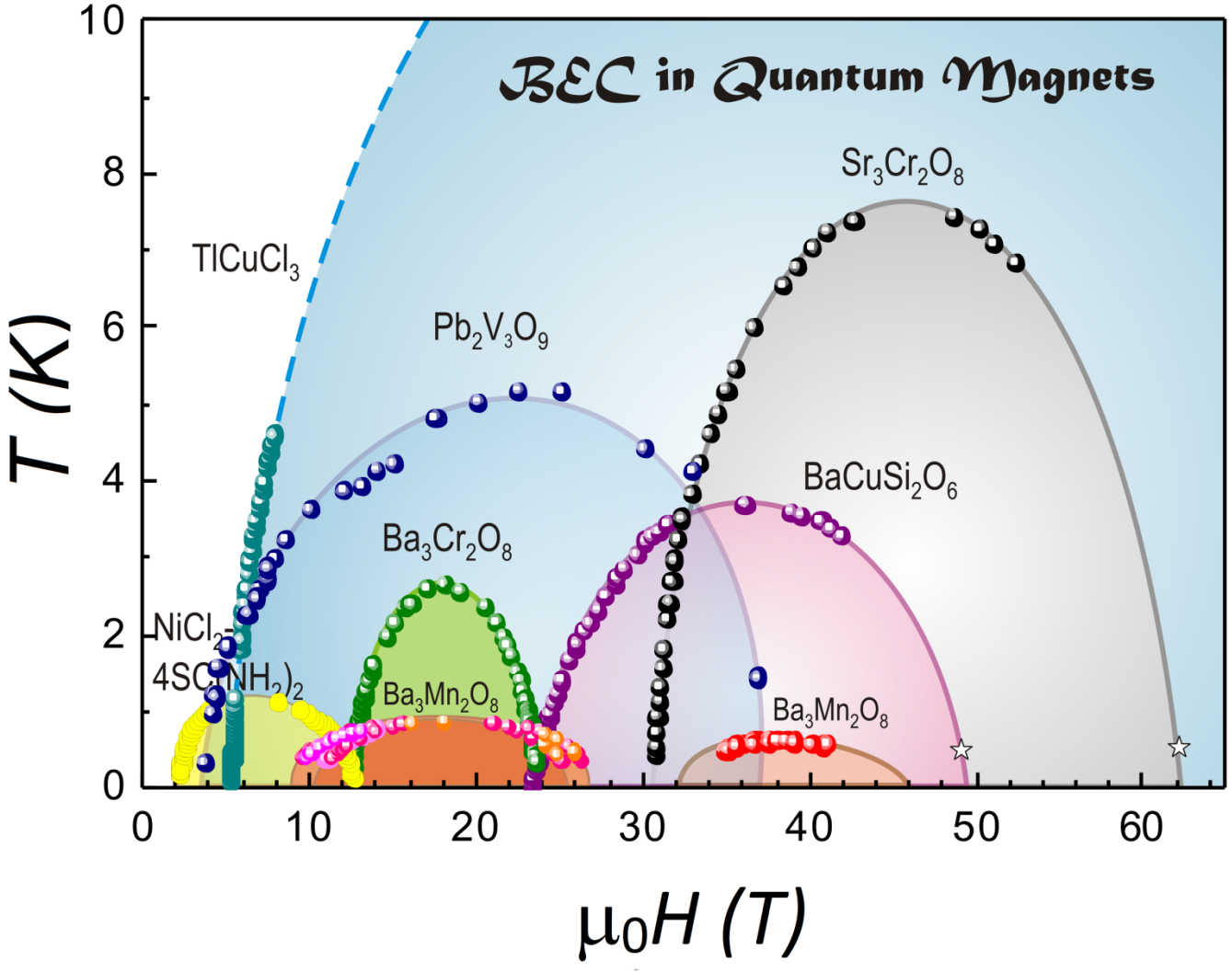
(ν tells us which **universe** electrons are in!)

Lambda transition in SPECIFIC HEAT due to XY Antiferromagnetism (≡ BEC) at temperatures as high as 3.9K

The S=1 dipole magnetic fields of the TRIPLONS become superfluid, moving without friction.

V. Zapf, M. Jaime, C.D. Batista. *Rev. Mod. Phys.* ***86***, *563* (2014)

When U(1) is the correct symmetry



V. Zapf, M. Jaime and C.D. Batista, "Bose-Einstein Condensation in Quantum Magnets", *Rev. Mod. Phys.* 86, 563 (2014)

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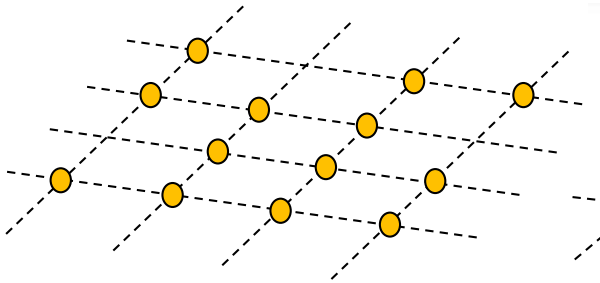
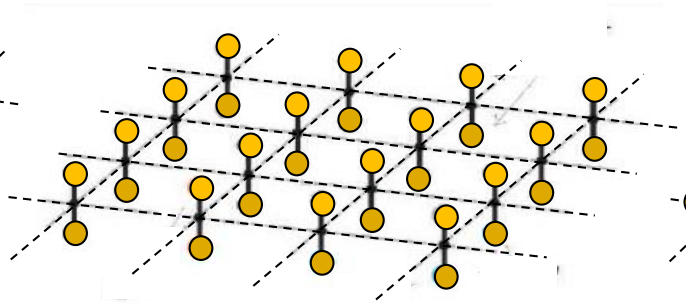
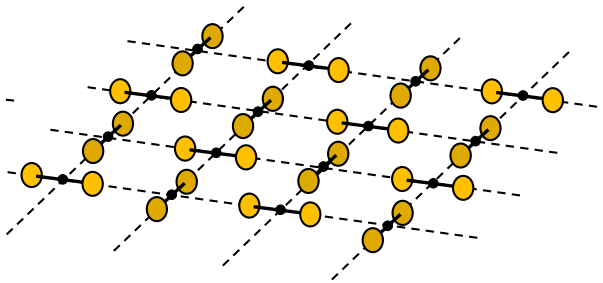
And different electron behaviors lead to different materials' properties.



Single-Layer of Electrons on Copper:
High Temperature Superconductor.
Electricity without Friction



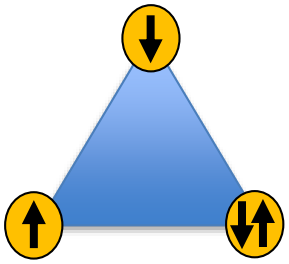
Double-Layer of Electrons on Copper
Magnetic Bose-Einstein condensation
Phase-coherent Magnetism
(without domain wall friction)



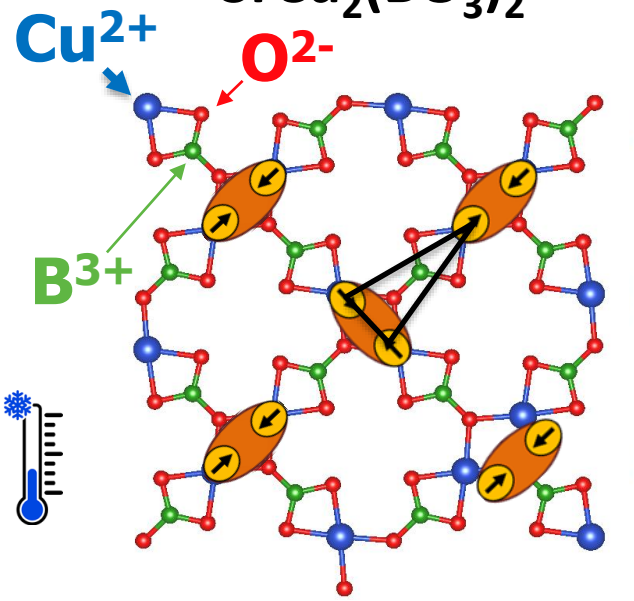
Double-density in a single layer
of Electrons on Copper
??????????

Frustrated Electrons on a Triangular Lattice:

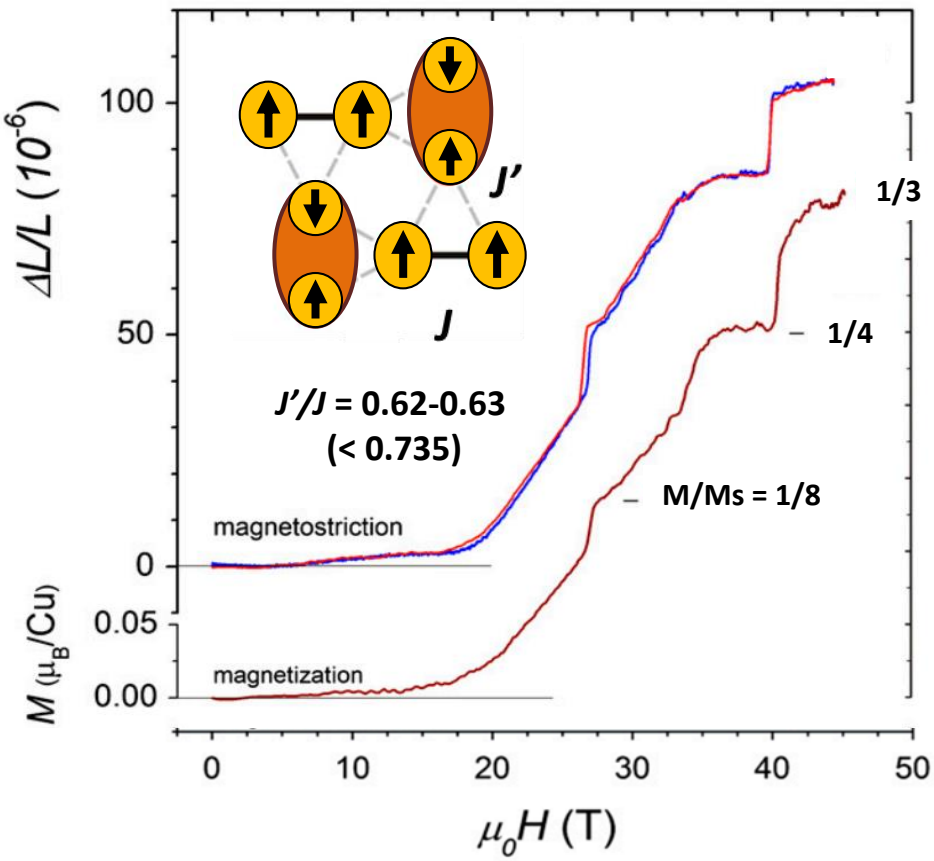
You can't satisfy all of the electrons all of the time.



$SrCu_2(BO_3)_2$



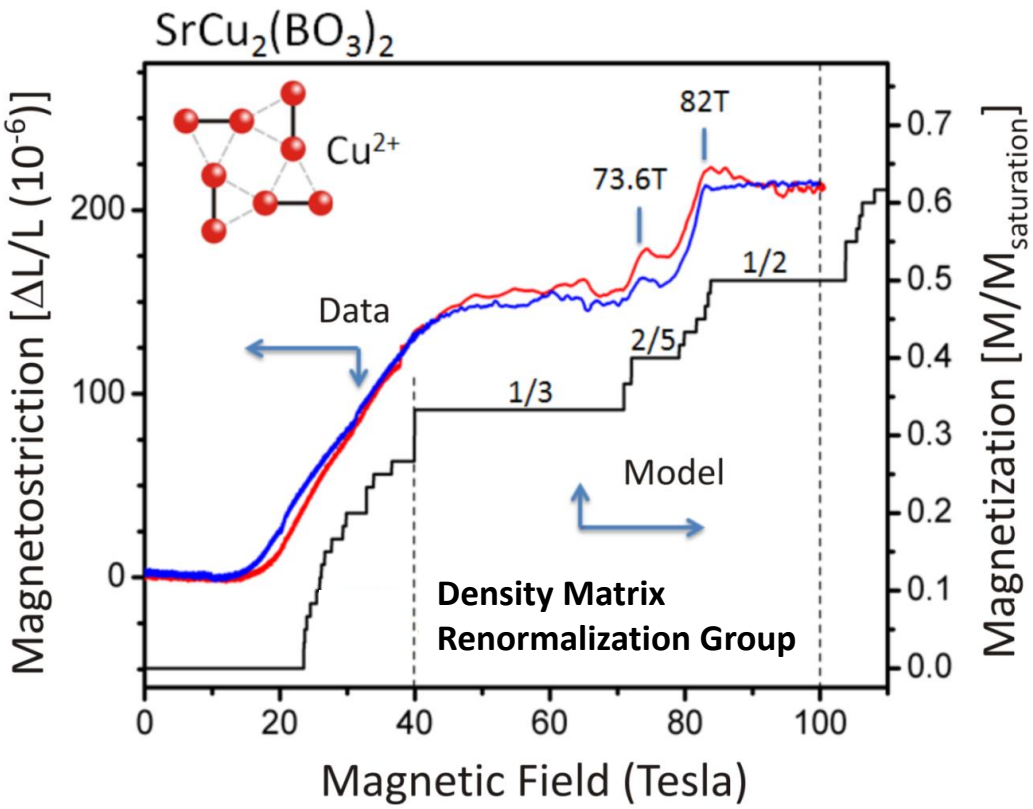
The simplest example of frustration: A triangle of three anti-ferromagnetically interacting Ising spins, each of which must point up or down.



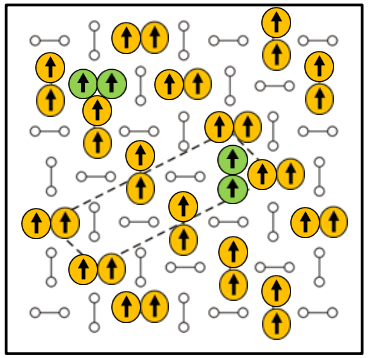
Smith & Kesler, J. Sol. St. Chem. 93, 430 (1991).
Kageyama et al., PRL 82, 3168 (1999).

B.S. Shastry & B. Sutherland, *Physica* 108B, 1069 (1981).

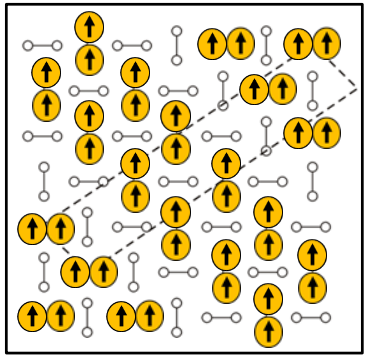
Extreme magnetic fields are needed to overlap *physical* against *numerical* experiments!



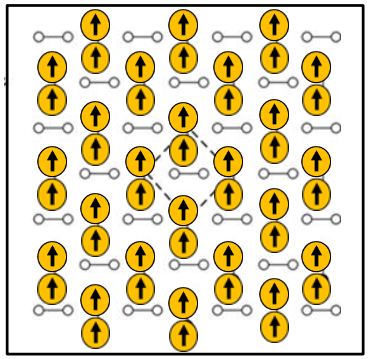
M/Ms =1/3



2/5

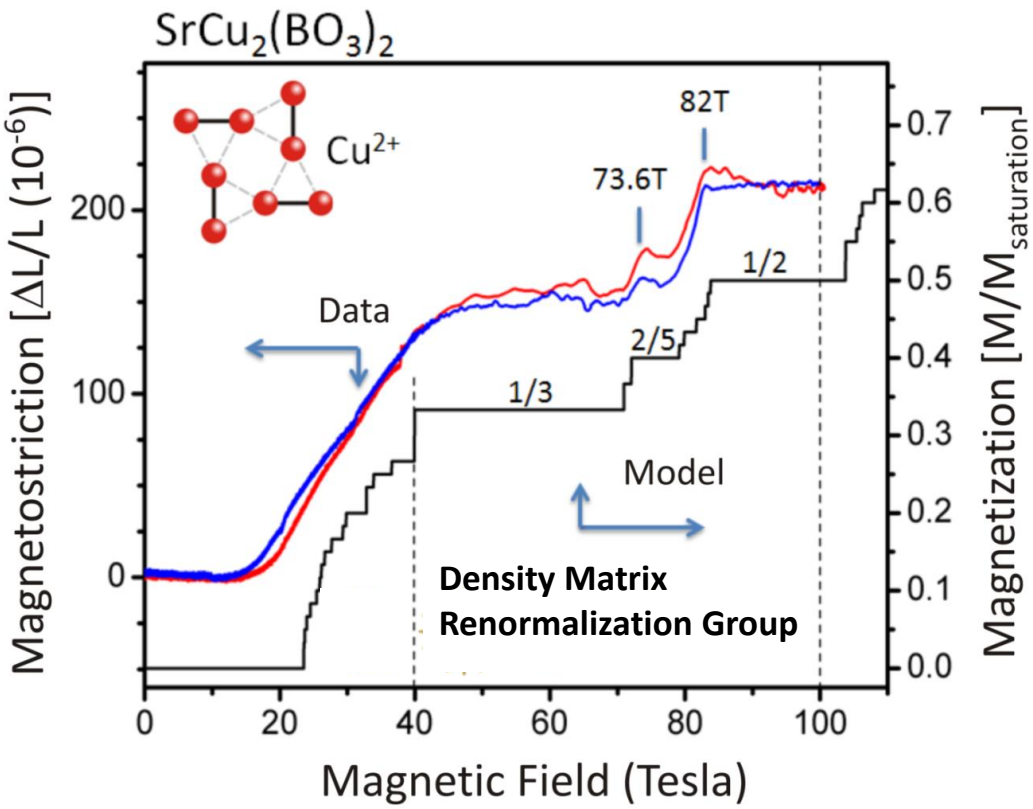


1/2

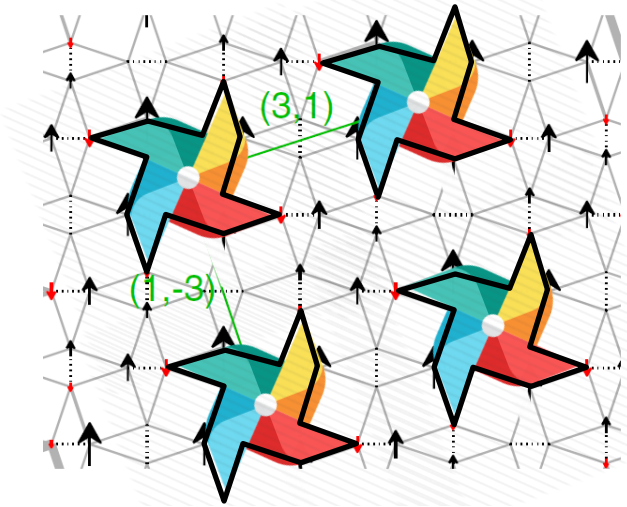


M. Jaime et al., *Proc. Natl. Acad. Science* 109, 120404 (2012)

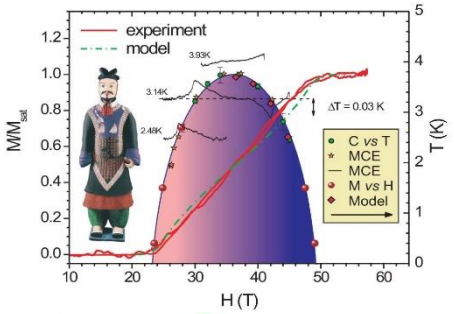
We know that real life is often more colorful than models.



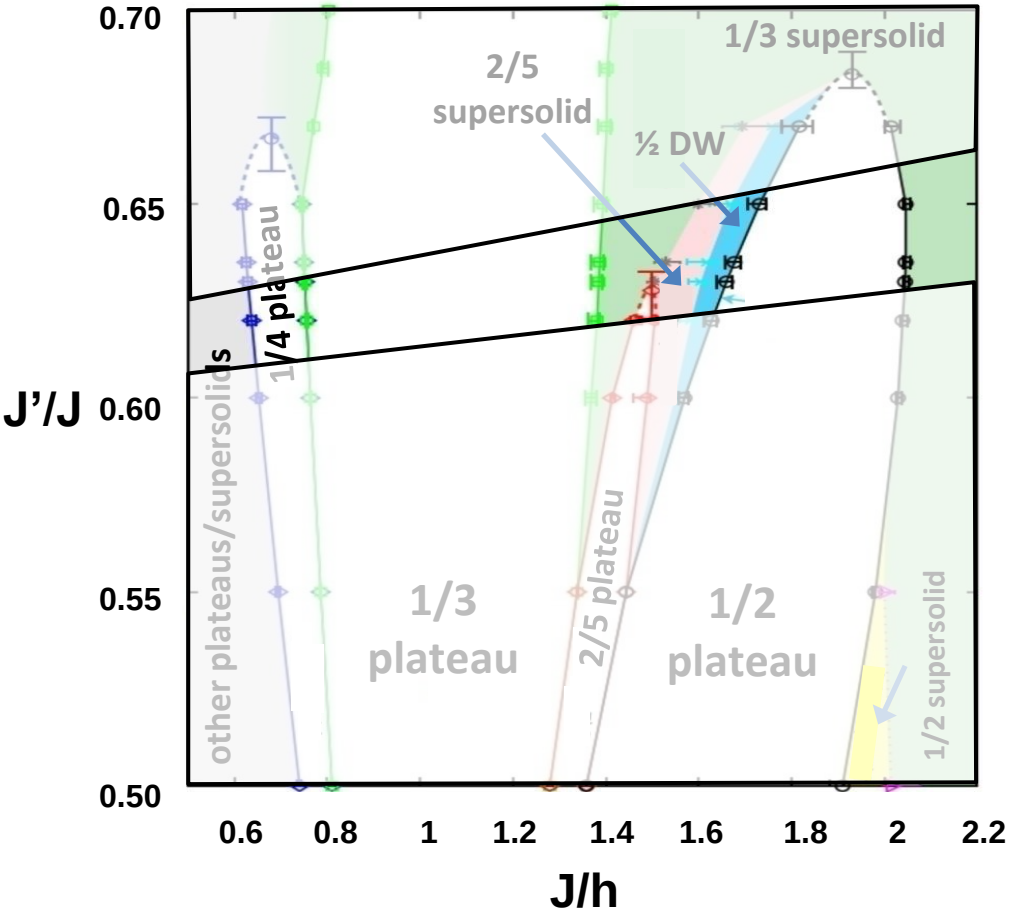
Plateaus → pinwheel pattern



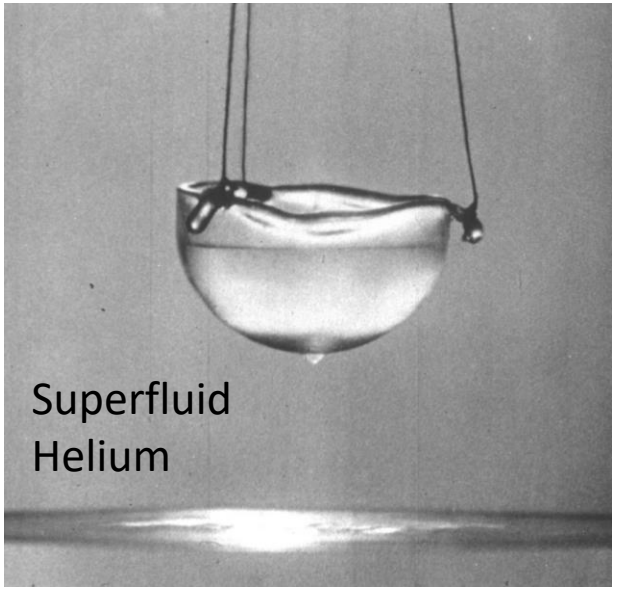
P. Corboz & F. Mila,
Phys. Rev. Lett. 112, 147203 (2014)



Frustration averts full coherence, yet by admitting diversity it spurs emergence of a new state of matter: the Supersolid State



A **supersolid** is a spatially ordered material with superfluid properties.



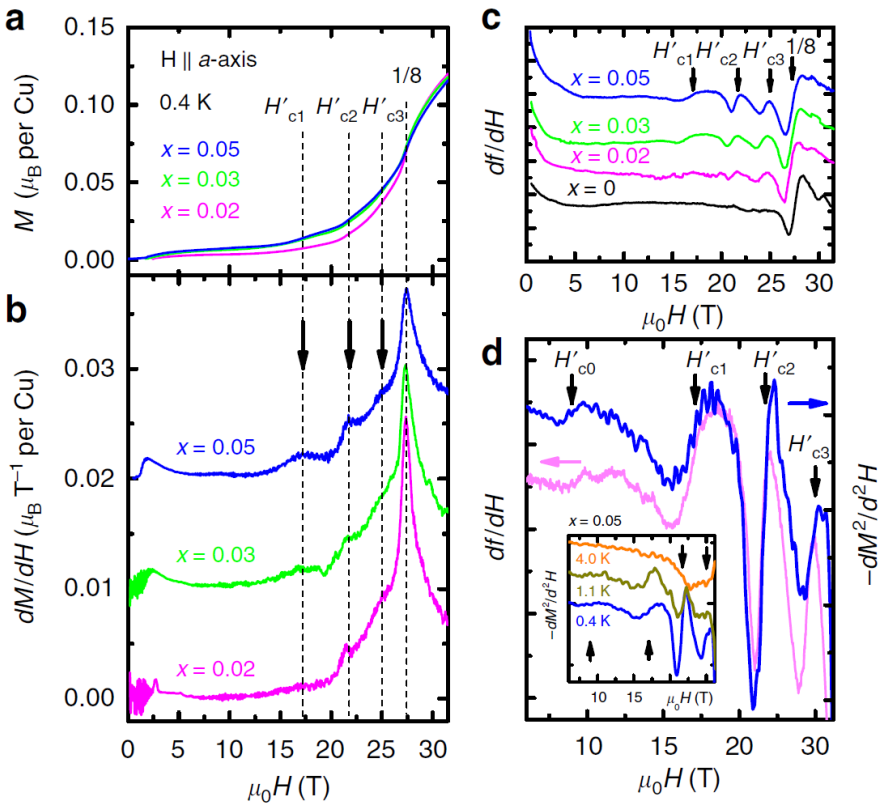
P. Sengupta & C.D. Batista, *Phys. Rev. Lett.*, 98, 227201 (2007)

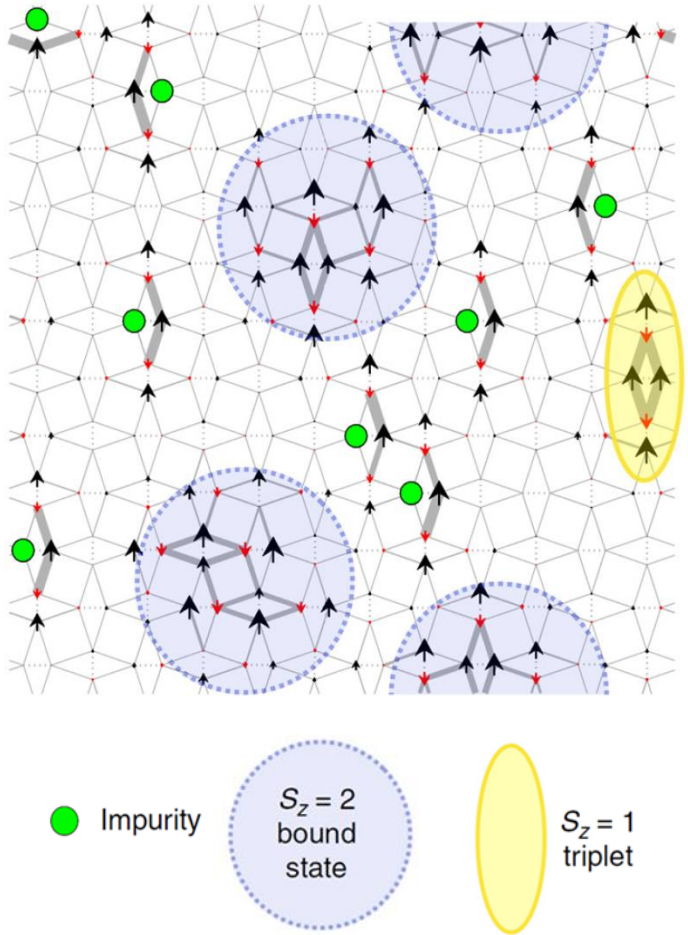
Y.H. Matsuda et al., *Phys. Rev. Lett.*, 111, 137204 (2013)

A. Saul et al., *unpublished*

Would doping lead to RVB superconductivity?

$$Mg^{2+} \rightarrow Cu^{2+} \quad : \quad SrCu_{2-x}Mg_x(BO_3)_2$$

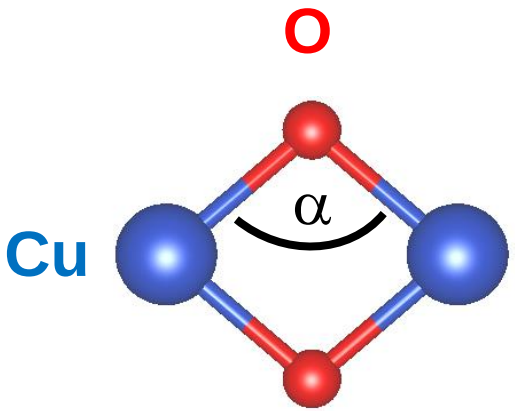




Z. Shi, M. Jaime, F. Mila, & S. Haravifard, et al., *Nature Comm.* 10, 2439 (2019)

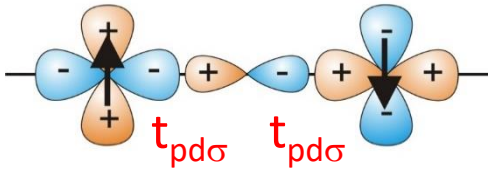
Magnetoelastic mechanism:

Goodenough-Kanamori

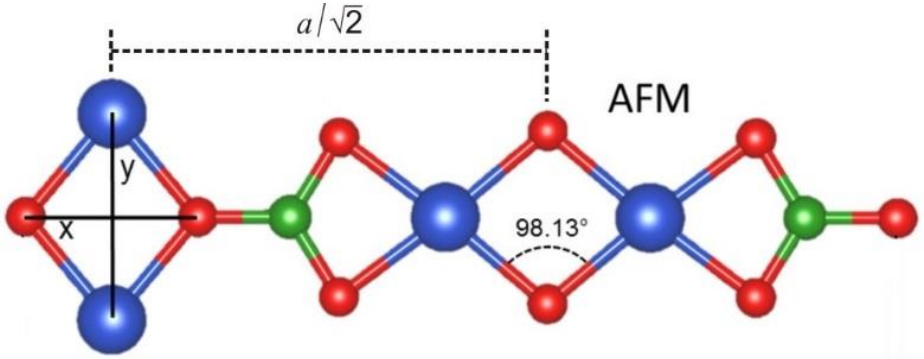


$\alpha = 98.8^{o}$

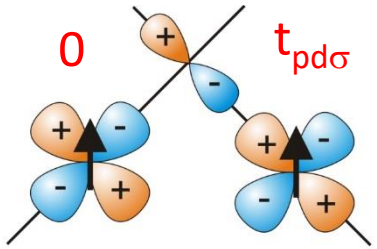
AFM >> FM



$\alpha = 180^{o}$



FM > AFM=0

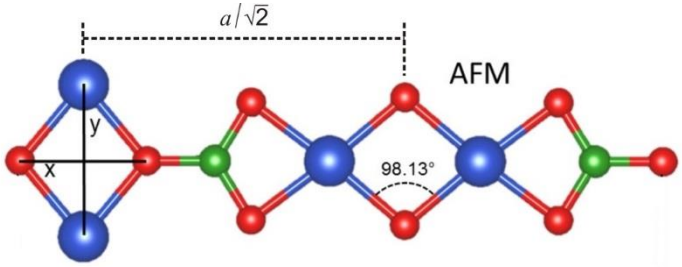


$\alpha = 90^{o}$

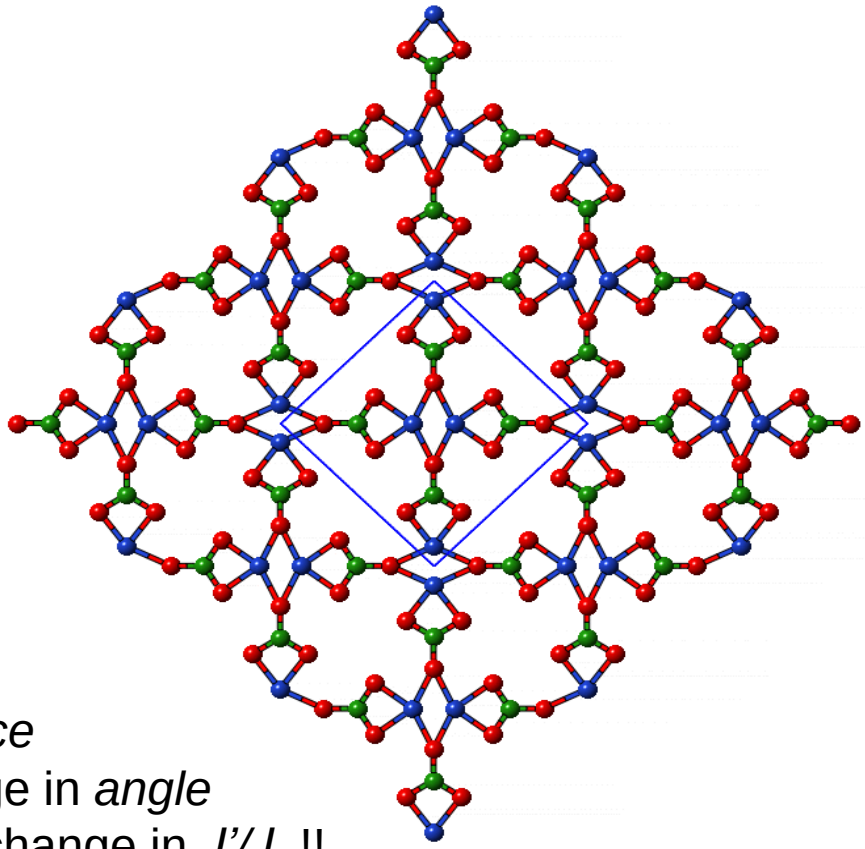
$$\Delta a = \frac{1}{\sqrt{2}}[\Delta x + \Delta y] \qquad \Delta\alpha = \frac{2xy}{x^2 + y^2}\left[\frac{\Delta y}{y} - \frac{\Delta x}{x}\right]$$

Y. Narumi, et al., *Jou. Phys. Soc. Jpn.* **78**, 043702 (2009).

Magnetic pantograph



- When magnetic field increases, Zeeman energy will impose a FM order
- But the energy cost is high because effective interactions are AFM
- The atoms responsible of the effective interactions will try to move to decrease them



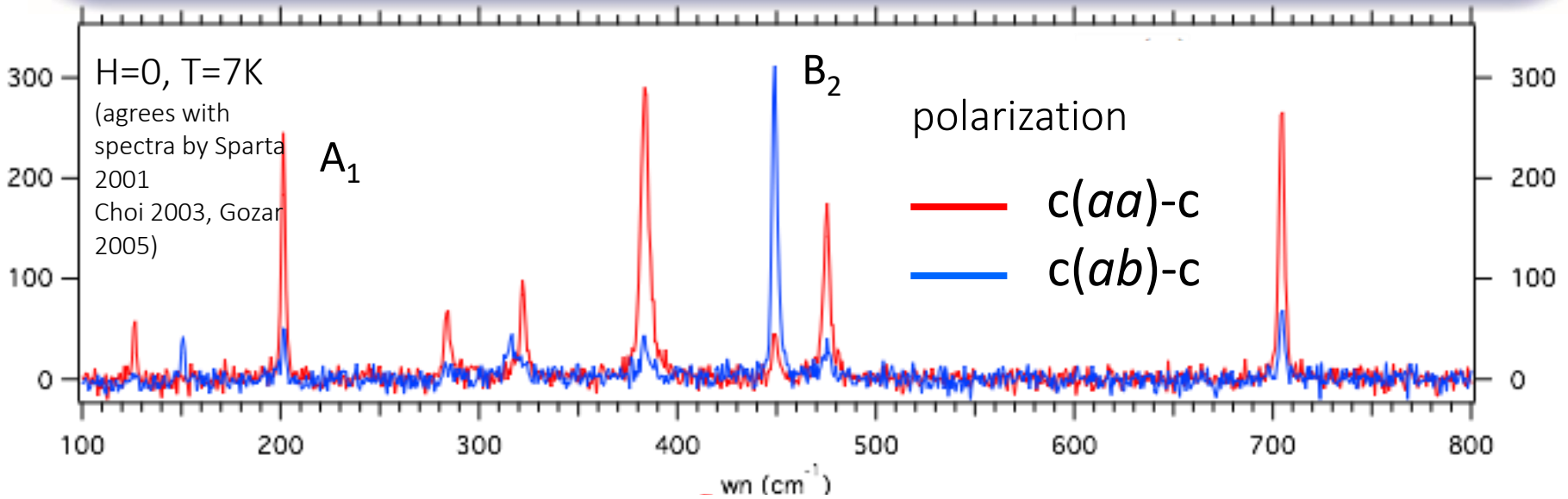
$$\Delta\alpha = 35\frac{\Delta a}{a}$$

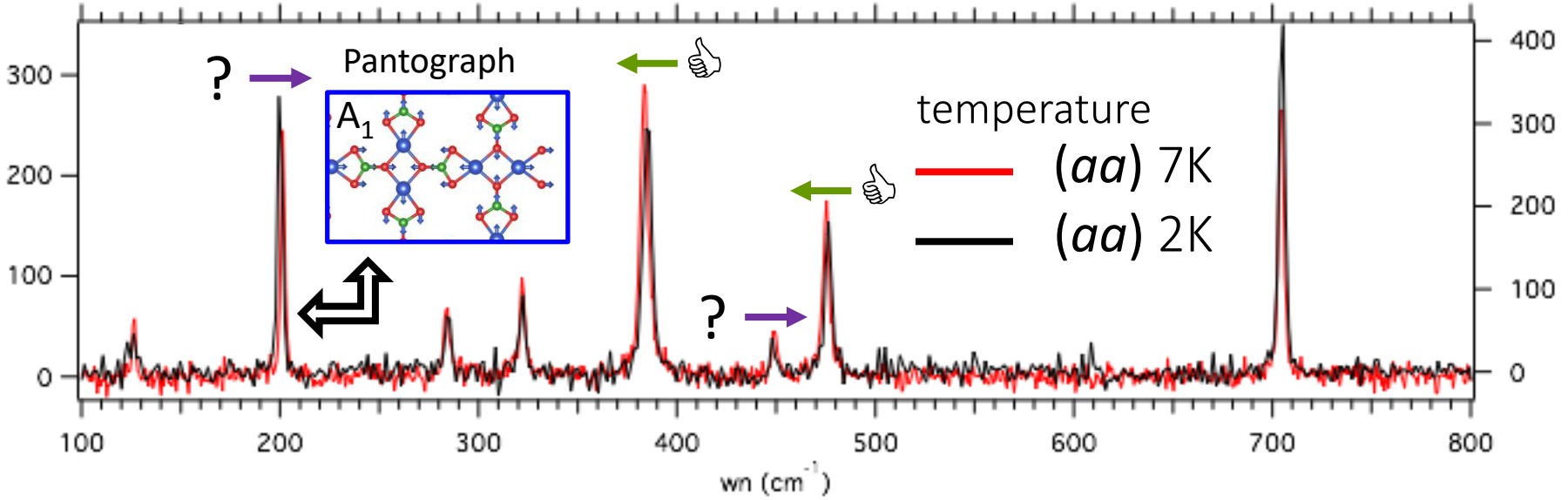
0.01% change in *lattice*
➔ 0.35 % change in *angle*
➔ 10 % change in *J'/J* !!

G. Radtke et al. *Proc. Natl. Acad. Science* 112, 1971 (2015).

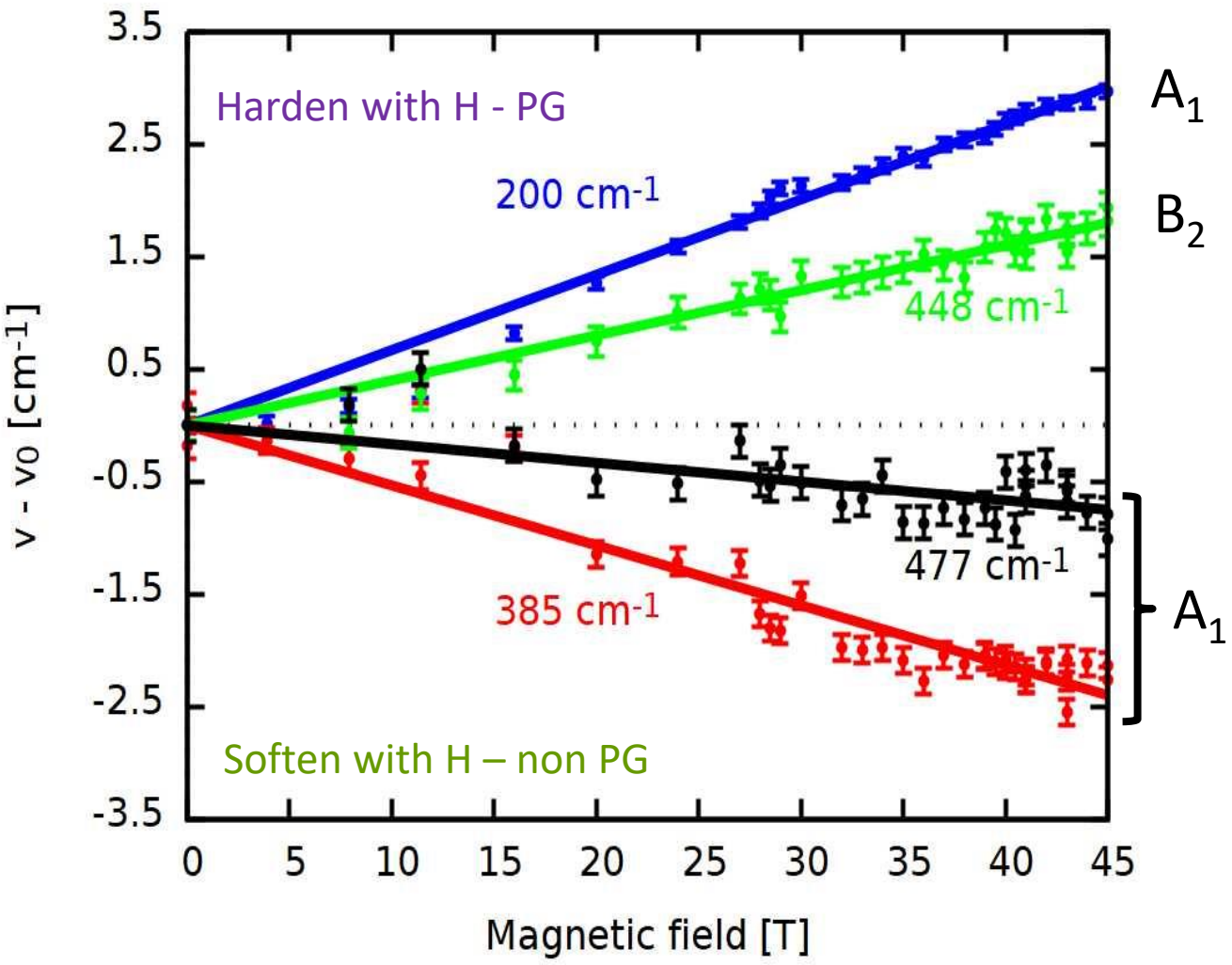
Raman scattering experiment, polarization & temperature

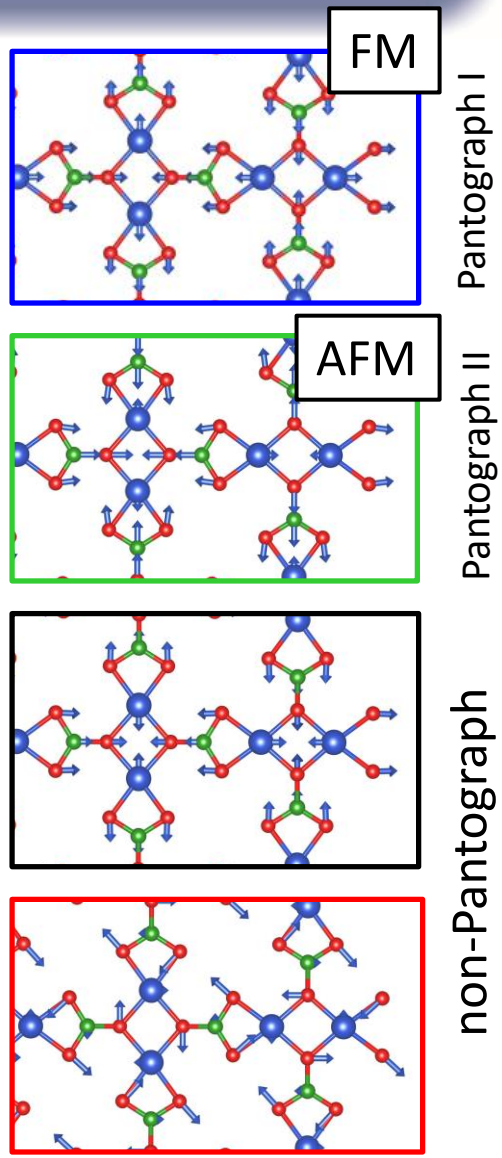
(Raman modes that shift in 2-7K range are likely coupled to spin gap)





Raman modes vs DC magnetic field to 45T



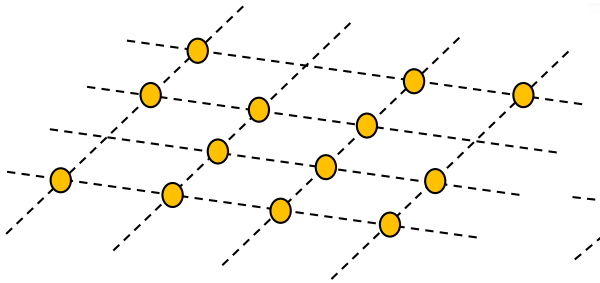


For an electron, every material is a different universe.

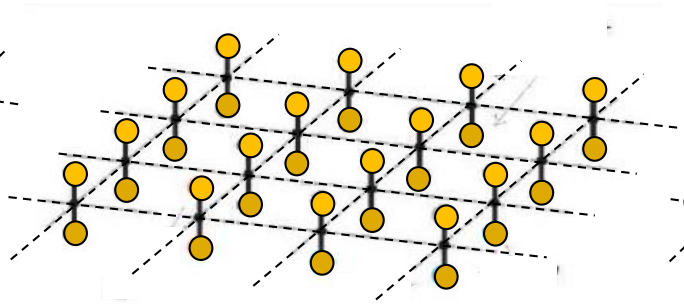
(GSB)

Astronomers Create 8 Million Baby Universes Inside a Computer and Watch Them Grow….
Behroozi et al., *MNRAS*, 488, 3143 (2019).

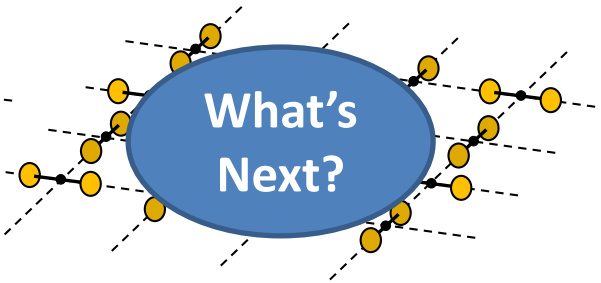
And different electron behaviors lead to different materials' properties.



Single-Layer of Electrons on Copper:
High Temperature Superconductor.
Electricity without Friction

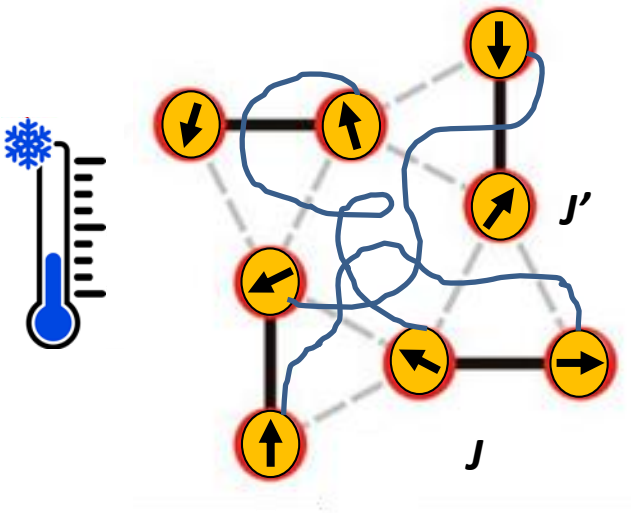


Double-Layer of Electrons on Copper
Magnetic Bose-Einstein condensation
Phase-coherent Magnetism
(without domain wall friction)



Double-density in a single layer
of Electrons on Copper
Supersolid state (NSM) between
stripe phases

What do we expect when frustration is <u>really</u> strong?



$J'/J \rightarrow 1$???

Wannier (1950) and Anderson (1973) proposed such a spin-disordered quantum state. *Candidate materials have, however, remained elusive …* until recently.

→ Quantum Spin Liquid

Figure credits: F.L. Pratt

- A **Quantum Spin Liquid** is a system with magnetic moments where there are no broken symmetries.

- It is a new state of matter found as T→0.
  - -The moments do not break translational symmetries, so they are like a liquid.
  - -There is no magnetic order, which is suppressed by quantum fluctuations.
  - -It is not a paramagnet. Interactions lead to long-ranged entanglement of the wave functions.

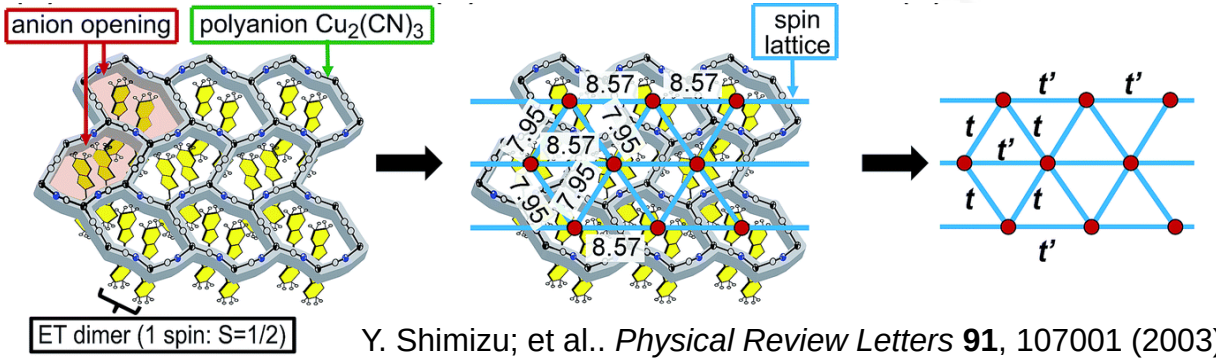
- The low energy properties of a Quantum Spin Liquid are related to effects such as:
  - -Quantum fluctuations
  - -Quantum entanglement
  - -Quantum coherence
  - -The topology of the quantum wave function.

- The signature properties of a Quantum Spin Liquid are not fully known, but they include:
  - -Nonlocal and topological excitations.
  - -Fractionalized excitations.
  - -'Nothingness' (absence of phase transitions, frustration parameter "*f*")

- QSL ground states may be topologically protected, suggesting possible role as qubits in quantum information applications.

Quantum Spin Liquid Candidates

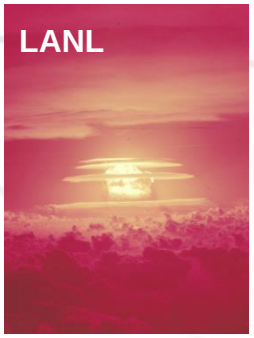
κ-$(ET)_2Cu_2(CN)_3$ ET : bis(ethylenedithio)tetrathiafulvalene

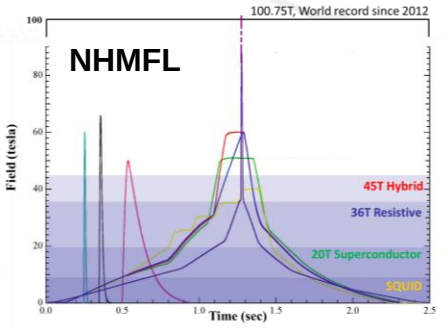


Y. Shimizu; et al.. *Physical Review Letters* **91**, 107001 (2003)

κ-$(BEDT\text{-}TTF)_2Cu_2(CN)_3$	$Rb_2Cu_3SnF_{12}$
$YbRh_2Si_2$	$1T\text{-}TaS_2$
$ZnCu_3(OH)_6Cl_2$ (herbertsmithite)	α-$RuCl_3$
$BaCu_3V_2O_8(OH)_2$ (vesignieite)	$Na_4Ir_3O_8$
Cu-(1,3-benzenedicarboxylate)	$PbCuTe_2O_6$
	$H_3LiIr_2O_6$

SUMMARY





- Brief History of Los Alamos National Laboratory
- Extreme Fields at the National High Magnetic Field Laboratory
- **Magnetic Quantum Matter** → Coherent spin states in **$BaCuSi_2O_6$**
- **Moderately frustrated MQM** → Coexistence and emergence:
  Supersolid states in **$SrCu_2(BO_3)_2$**
  Magnetic state robustness and “order from disorder” induced by doping
- **Strongly frustrated** MQM → search for topological quantum entangled state in Quantum Spin Liquids

BEC of triplons

Supersolid

Quantum Spin Liquid